Procedure for Identification and Investigation of Horizontal Curves with Insufficient Superelevation Rates

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Abstract

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A simple procedure was developed that can take several field measurements, including the superelevation rate, and convert them into the radius of the curve. These values can then be compared to design standards that are presented in charts for direct review in the field without the need for calculations or coming back to the office. This is an efficient field investigation of horizontal curves against current design standards. Another aspect of the investigation is a quick method to estimate whether or not SSD is provided through the curve.

Key Words
Horizontal Curve Field Procedure, Superelevation Rate, Radius Determination

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DISCLAIMER

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EXECUTIVE SUMMARY

NCDOT has the second largest highway mileage of any state in the nation. Many of these roads were constructed using older design standards for horizontal curves and superelevation that may not be suitable for current operating speeds and design standards. This is especially relevant for older two-lane, two-way highways, where perhaps hundreds of horizontal curves in each county may be affected by these new standards. A method is needed that can help NCDOT field engineers quickly and reliably evaluate the existing superelevation rate and radius for any curve against current AASHTO design standards which are adopted in the NCDOT Roadway Design Manual. Having a quick and reliable method will enable NCDOT to rapidly investigate any horizontal curve against current design standards and make recommendations for corrective action, if needed.

Of special concern is the change over time in the design standards as recommended by AASHTO in their book “A Policy on Geometric Design of Highways and Streets,” commonly referred to as the Green Book. These changing standards mean that previous designs may not meet current standards. One application of this is for horizontal curves, where the superelevation may not be enough for the intended speed of the vehicle. Another application is along the curve itself for safe stopping sight distance (SSD). Both of these issues impact the safety of the traveling public. There may be hundreds of substandard curves in each county that could be improved to meet current standards.

A simple procedure was developed that can take several field measurements, including the superelevation rate, and convert them into the radius of the curve. These values can then be compared to design standards that are presented in charts for direct review in the field without the need for calculations or coming back to the office. If a curve is found to be deficient, then the engineer can look at possible corrective action while on-site. This will be an extremely efficient field investigation of horizontal curves against current design standards. Another aspect of the investigation is a quick method to estimate whether or not SSD is provided through the curve.

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INTRODUCTION

NCDOT has the second largest highway mileage of any state in the nation. Many of these roads were constructed using older design standards for horizontal curves and superelevation that may not be suitable for current operating speeds and design standards. This is especially relevant for older two-lane, two-way highways, where perhaps hundreds of horizontal curves in each county may be affected by these new standards. A method is needed that can help NCDOT field engineers quickly and reliably evaluate the existing superelevation rate and radius for any curve against current American Association of State Highway and Transportation Officials (AASHTO) design standards which are adopted in the NCDOT Roadway Design Manual. Having a quick and reliable method will enable NCDOT to rapidly investigate any horizontal curve against current design standards and make recommendations for corrective action, if needed.

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A simple procedure was developed that can take several field measurements, including the superelevation rate, and convert them into the radius of the curve. The radius and measured values can then be compared to design standards through a set of charts for direct review in the field without the need for calculations or coming back to the office. If a curve is found to be deficient, then the engineer can look at possible corrective action while on-site. This will be an extremely efficient field investigation of horizontal curves against current design standards. Another aspect of the investigation is a quick method to estimate whether or not SSD is provided through the curve.

LITERATURE REVIEW

INTRODUCTION

The Chord Method can help NCDOT field engineers quickly and reliably evaluate the existing superelevation rate and radius for any curve against current AASHTO design standards. Documentation of literature findings on the best practices for crash reconstruction practices will also help in future investigations by NCDOT. AASHTO design superelevation criteria for maximum superelevation, design superelevation, design speed, and minimum radius were also examined.

STATE OF THE PRACTICE

Curve Investigation Techniques

An investigation in Texas compared the accuracy of ten curve radius estimating procedures (Carlson, Burris, Black, & Rose, 2005). The research compared each of the methods to the field survey which found that none of the methods were statistically inaccurate. The methods examined included:

- Basic ball bank indicator (BBI)
- Advanced BBI
- Chord length
- Compass
- Field survey
- Global Positioning System (GPS) unit
- Lateral acceleration
- Plan sheet
- Speed advisory plate
- Vehicle yaw rate

The advanced BBI and vehicle yaw rate methods were not examined past the initial stages of research. The GPS, plan sheet, and chord length methods had the smallest average relative errors of less than ±5%. A cost analysis was conducted for each of the techniques that were examined in detail (Exhibit 1). The plan sheet, speed advisory plate, compass, and chord length methods were each under $150 for the initial cost.

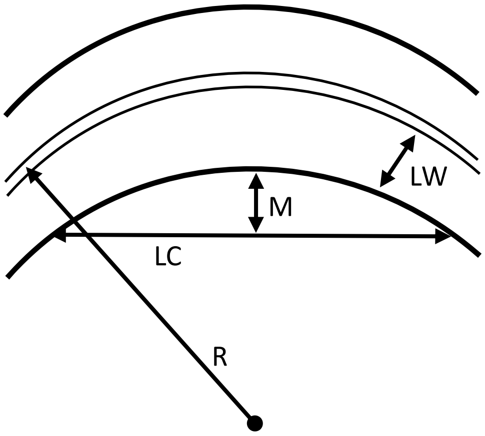
Exhibit 1: Radius Method Cost Analysis (Adapted from Carlson, et al 2005)

Method	**Initial Cost ($)**	**Cost Per Curve ($)**	
		10 Curves	**100 Curves**
Basic BBI	$560	$101	$51
Chord length	$145	$75	$62
Compass	$130	$28	$16
Field survey	$11,000	$1,220	$230
GPS unit	$530	$57	$9
Lateral acceleration	$5,600	$605	$101
Plan sheet	$0	$38	$38
Speed advisory plate	$15	$9	$8

Chord Method of Radius Estimation

The Chord Method is a method that allows a single investigator to determine the radius of a horizontal curve. The Chord Method functions as a viable one-person field investigation method by eliminating the need for determining the deflection angle, delta (Δ), of the horizontal curve. A survey crew is typically required to accurately determine delta, but a single person can execute the Chord Method. A chord (C, or LC) of known length should be placed between two points along the edge of the edge-line of the roadway. Each end of the chord must be within the limits of the curve (between the point of curvature and point of tangency of a single radius horizontal curve). At the mid-point of the chord, a measurement of the middle ordinate (M) should be taken from the chord to the edge of the edge-line. The lane width (LW) should also be measured at the time of the field investigation (Exhibit 2).

Exhibit 2: Horizontal Curve Layout



In order to determine the horizontal curve radius (R) without knowing the deflection angle (Δ), the following derivation and resulting equation can be utilized.

Starting with standard horizontal curve equations for Middle Ordinate (M) and Long Chord (LC):

$$M = R_{EL}\left(1-\cos\frac{\Delta}{2}\right) \quad \text{or} \quad \frac{M}{R_{EL}} = 1-\cos\frac{\Delta}{2}$$

$$LC = 2R_{EL}\sin\frac{\Delta}{2} \quad \text{or} \quad \frac{LC}{2R_{EL}} = \sin\frac{\Delta}{2}$$

Now, $\frac{M}{R_{EL}} = 1-\cos\frac{\Delta}{2}$ or $-1+\frac{M}{R_{EL}} = -\cos\frac{\Delta}{2}$

Multiply by -1: $1-\frac{M}{R_{EL}} = \cos\frac{\Delta}{2}$

Square Equation: $\left(1-\frac{M}{R_{EL}}\right)^2 = \left(\cos\frac{\Delta}{2}\right)^2$

Also: $\left(\frac{LC}{2R_{EL}}\right)^2 = \left(\sin\frac{\Delta}{2}\right)^2$

Recall: $(\sin\Delta)^2 + (\cos\Delta)^2 = 1$ $\left[\Delta\ can\ be\ \frac{\Delta}{2}\ as\ well\right]$

Thus: $\left(1-\frac{M}{\mathrm{R}_{EL}}\right)^2 + \left(\frac{LC}{2R_{EL}}\right)^2 = \left(\cos\frac{\Delta}{2}\right)^2 + \left(\sin\frac{\Delta}{2}\right)^2 = 1$

Expand: $1-\frac{2M}{\mathrm{R}_{EL}} + \frac{M^2}{R_{EL}{}^2} + \frac{LC^2}{4R_{EL}{}^2} = 1$

Simplify: $-\frac{2M}{\mathrm{R}_{EL}} + \frac{M^2}{R_{EL}{}^2} + \frac{LC^2}{4R_{EL}{}^2} = 0$

Multiply by R^2: $-2M\,\mathrm{R}_{EL} + M^2 + \frac{LC^2}{4} = 0$

Solve for R_{EL}: $R_{EL} = \frac{M^2 + 0.25LC^2}{2M}$

Therefore: $R = R_{EL} + LW$

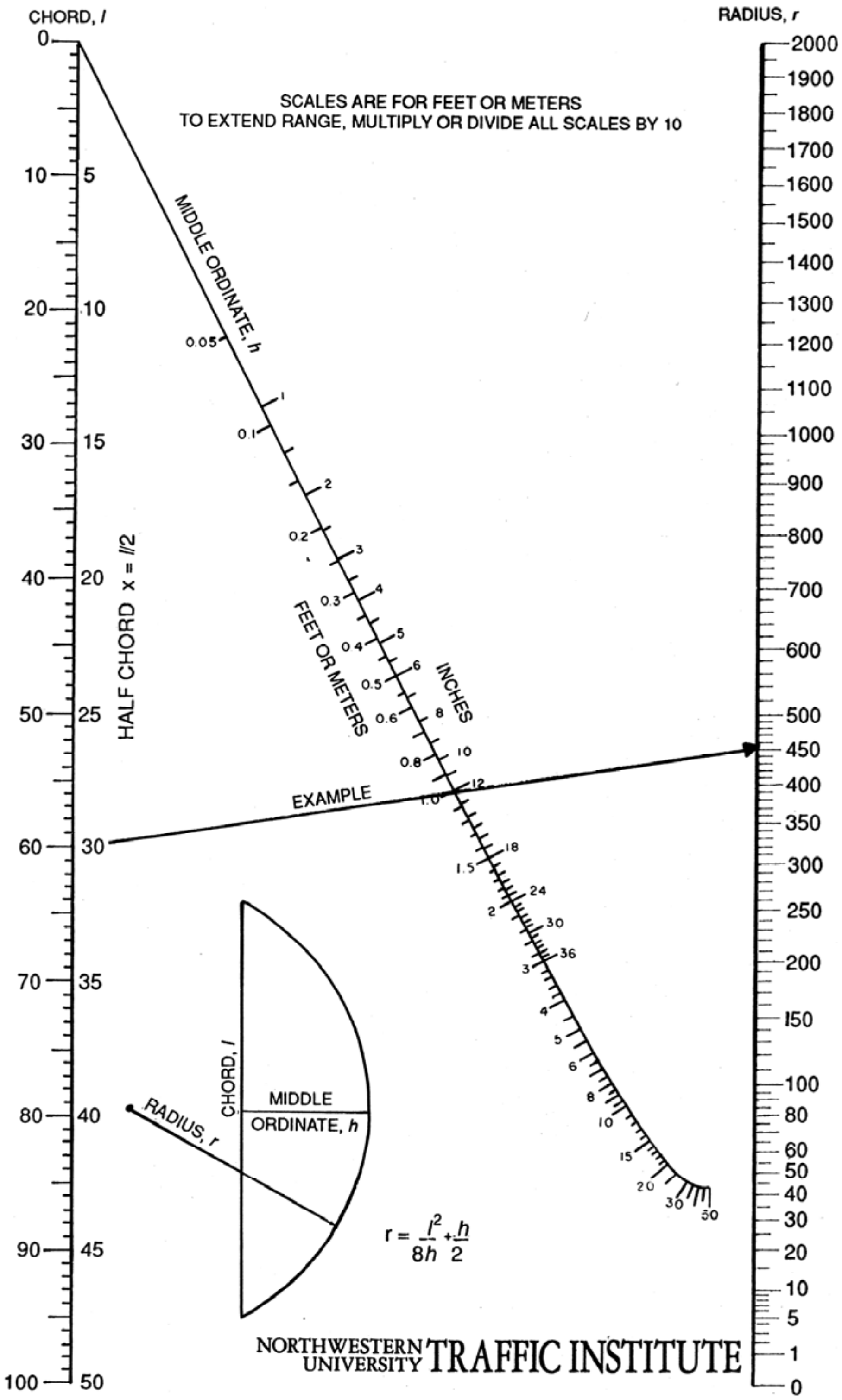
Final Equation (multiply by 4): $$R = \frac{4M^2 + C^2}{8M} + LW$$

Note that the long chord (LC) has been substituted with any chord length (C) in the final equation.

The final equation for determining the radius (R) of the centerline of the roadway is to add the lane width of the roadway to the radius of the edge-line, where C is a chord of known length, M is the middle ordinate distance measured at the midpoint of the chord, and LW is the measured lane width of the inside lane. The preceding derivation and equation are consistent with commonly accepted field procedures for establishing the radius of horizontal curves (Fricke, 1990; Carlson, Burris, Black, & Rose, 2005).

A nomograph developed by Northwestern University's Traffic Institute provides the ability for dynamic chord lengths (Fricke, 1990). The nomograph allows the user to use any chord length and its corresponding middle ordinate distance to determine the radius of the curve under investigation (Exhibit 3).

Exhibit 3: Northwestern University Traffic Institute Nomograph (Fricke, 1990)



AASHTO Green Book

One especially significant reason for doing this project is the recent change in the 2004 AASHTO Green Book on relating the minimum horizontal radius to the superelevation and coefficient of side friction (f) for a given design speed. The 2004 values for 'f' are much different at speeds ≤ 45 mph (AASHTO, 2004).

Exhibit 4: AASHTO Limiting Values of Coefficient of Side Friction

Design Speed (mph)	2001 AASHTO Limiting Values of 'f'	2004 AASHTO Limiting Values of 'f'
10	---	0.38
15	0.175	0.32
20	0.170	0.27
25	0.165	0.23
30	0.16	0.20
35	0.155	0.18
40	0.150	0.16
45	0.145	0.15
50	0.140	0.14
55	0.130	0.13
60	0.120	0.12
65	0.110	0.11
70	0.100	0.10
75	0.090	0.09
80	0.080	0.08

Now, with the new side friction values, the 2004 Green Book calculates the minimum radius to the nearest foot, without rounding up like the 2001 Green Book, as shown in Exhibit 5 for an 8.0% superelevation value.

Exhibit 5: AASHTO Minimum Radius (e_{max} 8%)

Design Speed (mph)	Maximum e (%)	2001 AASHTO Minimum R	2004 AASHTO Minimum R
10	8.0	---	14
15	8.0	60	38
20	8.0	105	76
25	8.0	170	134
30	8.0	250	214
35	8.0	350	314
40	8.0	465	444
45	8.0	600	587
50	8.0	760	758
55	8.0	965	960
60	8.0	1205	1200
65	8.0	1485	1480
70	8.0	1820	1810
75	8.0	2215	2210
80	8.0	2675	2670

Granted, these are minor differences, especially above 45 mph, but they do impact horizontal curve design. These values for minimum radius are a balance between the maximum superelevation and radius for a given design speed. If the radius is larger than the minimum, then the superelevation rate can be lowered to provide a new balance of the forces on the vehicle as it goes through the curve. The 2004 AASHTO Green Book uses a different approach than the 2001 version to correlate superelevation to radius. The 2004 version provides superelevation (e) on the left column and then the specific radius that matches that e for each design speed. The 2001 version provides a rounded radius on the left column and then shows the matching e needed for each design speed. And in both the 1965 and 1973 versions, degree of curve is on the left column with matching superelevation rates under each design speed. An example of the differences between these versions is shown in Exhibit 6 for 8% superelevation and 60 mph design speed.

Exhibit 6: AASHTO Radius Differences (e_{max} = 8%, Design Speed = 60 mph)

Superelevation (%)	1965 & 1973 Radius (ft)	2001 Radius (ft)	2004 Radius (ft)
NC	22,918	23,000 – 12,000	n/a
2.0	11,459	10,000	8,440
2.1	9,549 *	8,000	8,030 *
2.7	6,275 *	6,000	6,100 *
3.2	5,210 *	5,000	5,040
3.9	3,995 *	4,000	4,015 *
4.4	3,475 *	3,500	3,470
5.0	2,950 *	3,000	2,960
5.7	2,485 *	2,500	2,490 *
6.6	1,965 *	2,000	2,010
7.1	1,730 *	1,800	1,770 *
7.5	1,535 *	1,600	1,580 *
7.8	1,340 *	1,400	1,410
8.0	1,146	1,205	1,200

* Interpolated value

Again, these radii are close to each other, but not an exact match. Clearly there is judgment being left to the engineer on exactly what to use in each situation if there is not a perfect match between radius and e for a specific curve layout.

Another aspect of the problem is the recent change in the 2001 AASHTO Green Book for stopping sight distance (SSD) calculation. This formula has changed and a new rate of deceleration is applied. The new formula is: $SSD = 1.47Vt + 1.075\frac{V^2}{a}$

Where, SSD = stopping sight distance, ft

V = design speed, mph

t = brake reaction time, 2.5 s

a = deceleration rate, 11.2 ft/s^2

Thus, new SSD values are calculated for each design speed as shown in Exhibit 7.

Exhibit 7: AASHTO Stopping Sight Distance Differences

Design Speed (mph)	1965 AASHTO Min. Design SSD (ft)	1973 AASHTO Min. Design SSD (ft)	1984 AASHTO Min. Design SSD (ft)	2001 AASHTO Min. Design SSD (ft)
15	---	---	---	80
20	---	---	125	115
25	---	---	150	155
30	200	200	200	200
35	---	---	250	250
40	275	275	325	305
45	---	---	400	360
50	350	350	475	425
55	---	---	550	495
60	475	475	650	570
65	550	550	725	645
70	600	600	850	730
75	675	---	---	820
80	750	---	---	910

As can be seen, differences in SSD occur for all but two design speeds, 30 and 35 mph, between the 1984 and 2001 Green Books. Most of the highways where there may be problems with superelevation would be on highways with posted speed limits greater than 40 mph. These values are also different for many design speeds based on earlier versions of the AASHTO Green Book (red cover in 1973 and blue cover in 1965).

These new SSD values are then entered into formulas for determining the minimum length of vertical curve needed to satisfy SSD criteria and can be correlated to the appropriate horizontal curve radius that satisfies SSD criteria as well.

Design inconsistencies in the AASHTO Green Book have been identified in previous research. The selection of different maximum superelevation rates in the Green Book affects superelevation rate although the actual design speed and radius are identical. A superelevation distribution method that accounts for design speed, radius and superelevation rate was developed to overcome the discrepancies in the Green Book (Bonneson, 2001). However, it is unclear if this method has been adopted by any agency.

What does all this mean for NCDOT? Since 1933 when the State Highway Commission was created, there have been construction efforts to pave unpaved roads and construct new roads to get the citizens of the state out of the mud. Design standards have evolved over time, with slight variations as each new version of the AASHTO Green Book is published. When the need arises, an engineer's field investigation that checks horizontal curvature against superelevation must be based on sound engineering principles that meet current design standards.

Crash Reconstruction

A primary application of a field procedure for identifying and investigating horizontal curves with insufficient superelevation rates is crash reconstruction. The National Cooperative Highway Research Program (NCHRP) Synthesis 369 is a valuable resource of the practices of state DOT crash reconstruction (NCHRP 369, 2007). NCHRP Synthesis 369 provides a state of the practice summary of the involvement and procedures of state departments of transportation in crash reconstruction. The researchers utilized a survey, local technical assistance inquires, and website searches to acquire the pertinent information.

The research found that about 26% (11 of 43) of the DOTs are routinely involved in crash reconstruction with a designated unit or consultant[1]. Other DOTs reported that consultants were utilized in response to lawsuits. The number of employees involved in the crash reconstructions varied from one to eight across the survey respondents. In some court cases, expert witnesses were hired by state DOTs that had designated units. Reconstructions were conducted immediately after the incident, or months or years later in some cases.

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[1] California, Delaware, Kansas, Kentucky, Louisiana, New Mexico, Nevada, North Carolina, Oklahoma, Pennsylvania, and, West Virginia

RECOMMENDED CURVE INVESTIGATION METHOD

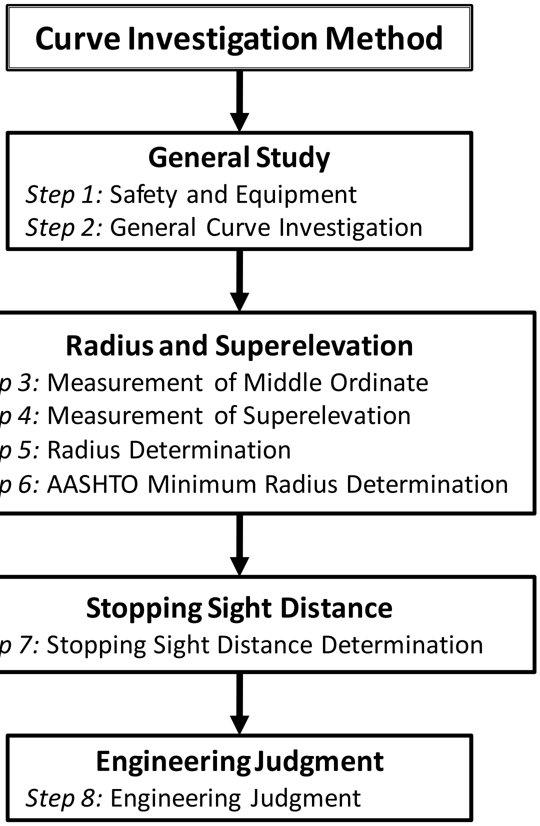
The research team visited nine curve locations in Wake County to observe the variability of curve characteristics and understand the limitations of investigation applications. The procedures were developed with field condition considerations for the parameters of radius, superelevation, and stopping sight distance. The eight-step procedure is fully contained in Appendix A along with the Field Investigation Form. The aim of the procedure was to be time and cost-efficient for implementation by a single person.

Of particular interest during the initial trials is the finding that a 50′ chord length was the easiest to use in the field. It provided a long enough length to measure a middle ordinate for some longer radii, while still being very manageable in stretching out the tape to get it taught. Other chord lengths tried included 30′ and 40′ lengths, but these were generally felt to be too short unless the radius was small, say under 200 feet.

The following steps, including the overall categories shown in Exhibit 8 (General Study, Radius and Superelevation, Stopping Sight Distance, and Engineering Judgment), will provide the procedural steps and the conceptual or computational background for the completion of the field investigation for each of the curve characteristics of interest.

The first two steps are general guidelines for following appropriate safety precautions and the proper equipment needed for the study (step 1) and general curve investigation guidelines (step 2). The radius is a key parameter for describing a curve and for comparisons to standard design guidelines. The radius can be determined by using a chord that is within the curve limits and the corresponding middle ordinate value of the chord. The superelevation of the curve is used to compare the radius to AASHTO design recommendations. Four steps provide the instructions for the investigation of curve radius and superelevation. Step 3 details the method for determining the middle ordinate distance. Step 4 describes the method for determining the superelevation of the curve. Step 5 provides the information for converting the middle ordinate distance into a radius value. Step 6 determines the AASHTO minimum recommended radius which can be compared to the field measured value. Step 7 provides the investigator with a method to determine if stopping sight distance is a concern through the horizontal curve. Step 8 provides concluding information about the study procedure and the importance of engineering judgment.

Exhibit 8: Curve Investigation Method



1. Safety and Equipment – Before beginning any field investigation, check that all equipment is available and operable. Although this procedure was developed to minimize exposure to vehicles, some interaction is necessary, so follow NCDOT guidelines for personal safety while implementing this field procedure. Necessary equipment includes:
    a. Safety Vest (Class II or above as required)
    b. Digital Level (4′ long)
    c. Hammer
    d. Masonry Nails (e.g., Parker-Kalon 1½″ by ¼″)
    e. Measuring Tape (50′ or 100′ Metal or Cloth, with metal preferred)
    f. Metal Tape Measure (25′)
    g. Clipboard, Field Investigation Form, and Pen
    h. Three Orange Traffic Cones (2′ tall)
    i. Measuring Wheel

2. General Curve Investigation – Determine the limits (Point of Curvature, PC, and Point of Tangency, PT) of the curve through visual observations of the tangent sections leading into and out of the curve. All measurements should occur within these limits of the curve. Try to locate representative areas of the curve to conduct your measurements, avoiding any abnormalities. The first measurement should be about in the middle of the curve.

3. Measurement of Middle Ordinate – Determine the middle ordinate measurement through the following steps:
    a. Place nails in the pavement on the outside edge of the edgeline stripping 50′ apart (at points 1 and 2 in Exhibit 9). One nail can be used to hold the hook at the end of the 50′ measuring tape and the second nail can be used to pull the tape against or around (if cloth tape is used). The tape must be pulled taught and remain straight for step 3b.
    b. Measure the middle ordinate distance at the middle point of the tape (25′), using the smaller tape measure (at point 3 in the figure). The distance M should be read and recorded to the nearest 1/8″.
    c. Repeat this measurement by moving points 1 and 2 together about 10 feet left and then 10 feet right of the first measurement. This provides three measurements.

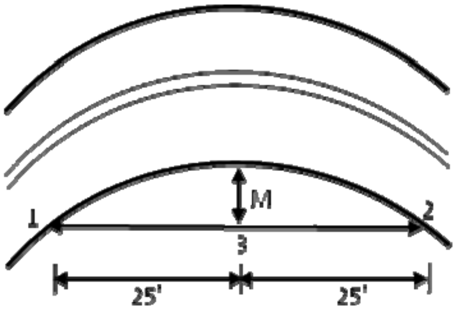
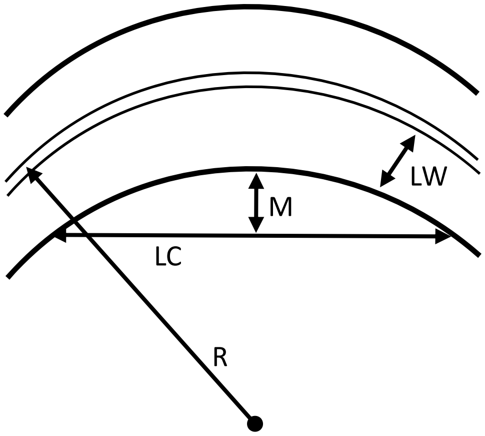


Exhibit 9: Middle Ordinate Measurement

4. Measurement of Superelevation – Determine the superelevation of the curve by measuring the superelevation of the roadway perpendicular to the direction of travel by reading and recording five measurements that are representative of the superelevation of the middle section of the curve in each lane. Circle the median value, which will be used as the superelevation value. This value must be in increments of 0.2% as represented in the AASHTO Minimum Radius Tables. If necessary, round the field measured value up or down to the nearest 0.2% increment.

5. Radius Determination – Determine the radius of the curve by using the circled middle ordinate value from the Field Investigation Form and the Middle Ordinate Conversion Table (Exhibit 11). Add the inside lane width to the table value to determine the centerline radius of the curve. Record the value on the Field Investigation Form. Exhibit 10 provides a visual display of the parameters used to determine the radius.

Exhibit 10: Curve Radius Determination



$$R = \frac{M^2 + 0.25LC^2}{2M} + LW$$

Where:

R = Radius (feet)

M = Middle Ordinate (feet)

LW = Lane Width (feet)

LC = Long Chord (feet)

Exhibit 11: Middle Ordinate Conversion Table

Middle Ordinate Conversion Table							
Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft	Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft	Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft	Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft
0.125	30,000	2.625	1,429	5.25	715	10.25	366
0.250	15,000	2.750	1,364	5.50	682	10.50	358
0.375	10,000	2.875	1,304	5.75	652	10.75	349
0.500	7,500	3.000	1,250	6.00	625	11.00	341
0.625	6,000	3.125	1,200	6.25	600	11.25	334
0.750	5,000	3.250	1,154	6.50	577	11.50	327
0.875	4,286	3.375	1,111	6.75	556	11.75	320
1.000	3,750	3.500	1,072	7.00	536	12.00	313
1.125	3,333	3.625	1,035	7.25	518	12.25	307
1.250	3,000	3.750	1,000	7.50	500	12.50	301
1.375	2,727	3.875	968	7.75	484	12.75	295
1.500	2,500	4.000	938	8.00	469	13.00	289
1.625	2,308	4.125	909	8.25	455	13.25	284
1.750	2,143	4.250	883	8.50	442	13.50	278
1.875	2,000	4.375	857	8.75	429	13.75	273
2.000	1,875	4.500	834	9.00	417	14.00	268
2.125	1,765	4.625	811	9.25	406	14.25	264
2.250	1,667	4.750	790	9.50	395	14.50	259
2.375	1,579	4.875	769	9.75	385	14.75	255
2.500	1,500	5.000	750	10.00	375	15.00	251

Note: Add inside lane width to radius value from table to find centerline radius for a two-lane highway.

6. AASHTO Minimum Radius Determination – Determine the minimum recommended radius of the curve by using the circled superelevation value from the Field Investigation Form and the appropriate AASHTO Minimum Radius Table (for an e_{max} of 4%, 6%, or 8%). Record the value on the Field Investigation Form. The AASHTO Minimum Radius for the inside lane and outside lane will be equal if the superelevations for each lane are equal.

The selection of the appropriate e_{max} value is important. Shoulder sections of two-lane roadways should have a design superelevation of 8% for higher speed segments or 6% for lower speed segments. The comparison can be examined for both design superelevations, if necessary. A design superelevation of 4% should be used for curb and gutter sections of urban roadways. Additional maximum superelevation rate guidance is available from the NCDOT Roadway Design Manual – Part 1, Chapter 1: General Design.

Exhibit 12: AASHTO Minimum Radius Table (e_{max} = 4%)

AASHTO Minimum Radius Table (e_{max} = 4%)					
Superelevation, e (%)	Posted Speed Limit, V_d (mph)				
	35	40	45	50	55
	Radius (ft)				
1.5	3,730	4,770	5,930	7,220	8,650
2.0	2,490	3,220	4,040	4,940	5,950
2.2	2,120	2,760	3,480	4,280	5,180
2.4	1,760	2,340	2,980	3,690	4,500
2.6	1,420	1,930	2,490	3,130	3,870
2.8	1,170	1,620	2,100	2,660	3,310
3.0	982	1,370	1,800	2,290	2,860
3.2	835	1,180	1,550	1,980	2,490
3.4	714	1,010	1,340	1,720	2,170
3.6	610	865	1,150	1,480	1,880
3.8	512	730	970	1,260	1,600
4.0	371	533	711	926	1,190

Source: AASHTO *A Policy on Geometric Design of Highways and Streets* 2004

Exhibit 13: AASHTO Minimum Radius Table (e_{max} = 6%)

AASHTO Minimum Radius Table (e_{max} = 6%)

Superelevation, e (%)	Posted Speed Limit, V_d (mph)				
	35	40	45	50	55
	Radius (ft)				
1.5	4,100	5,230	6,480	7,870	9,410
2.0	2,950	3,770	4,680	5,700	6,820
2.2	2,630	3,370	4,190	5,100	6,110
2.4	2,360	3,030	3,770	4,600	5,520
2.6	2,130	2,740	3,420	4,170	5,020
2.8	1,930	2,490	3,110	3,800	4,580
3.0	1,760	2,270	2,840	3,480	4,200
3.2	1,600	2,080	2,600	3,200	3,860
3.4	1,460	1,900	2,390	2,940	3,560
3.6	1,320	1,740	2,190	2,710	3,290
3.8	1,190	1,590	2,010	2,490	3,040
4.0	1,070	1,440	1,840	2,300	2,810
4.2	960	1,310	1,680	2,110	2,590
4.4	868	1,190	1,540	1,940	2,400
4.6	788	1,090	1,410	1,780	2,210
4.8	718	995	1,300	1,640	2,050
5.0	654	911	1,190	1,510	1,890
5.2	595	833	1,090	1,390	1,750
5.4	540	759	995	1,280	1,610
5.6	487	687	903	1,160	1,470
5.8	431	611	806	1,040	1,320
6.0	340	485	643	833	1,060

Source: AASHTO *A Policy on Geometric Design of Highways and Streets* 2004

Exhibit 14: AASHTO Minimum Radius Table (e_{max} = 8%)

AASHTO Minimum Radius Table (e_{max} = 8%)

Superelevation, e (%)	Posted Speed Limit, V_d (mph)				
	35	40	45	50	55
	Radius (ft)				
1.5	4,260	5,410	6,710	8,150	9,720
2.0	3,120	3,970	4,930	5,990	7,150
2.2	2,800	3,570	4,440	5,400	6,450
2.4	2,540	3,240	4,030	4,910	5,870
2.6	2,320	2,960	3,690	4,490	5,370
2.8	2,130	2,720	3,390	4,130	4,950
3.0	1,960	2,510	3,130	3,820	4,580
3.2	1,820	2,330	2,900	3,550	4,250
3.4	1,690	2,170	2,700	3,300	3,970
3.6	1,570	2,020	2,520	3,090	3,710
3.8	1,470	1,890	2,360	2,890	3,480
4.0	1,370	1,770	2,220	2,720	3,270
4.2	1,280	1,660	2,080	2,560	3,080
4.4	1,200	1,560	1,960	2,410	2,910
4.6	1,130	1,470	1,850	2,280	2,750
4.8	1,060	1,390	1,750	2,160	2,610
5.0	991	1,310	1,650	2,040	2,470
5.2	929	1,230	1,560	1,930	2,350
5.4	870	1,160	1,480	1,830	2,230
5.6	813	1,090	1,390	1,740	2,120
5.8	761	1,030	1,320	1,650	2,010
6.0	713	965	1,250	1,560	1,920
6.2	669	909	1,180	1,480	1,820
6.4	628	857	1,110	1,400	1,730
6.6	590	808	1,050	1,330	1,650
6.8	553	761	990	1,260	1,560
7.0	518	716	933	1,190	1,480
7.2	485	672	878	1,120	1,400
7.4	451	628	822	1,060	1,320
7.6	417	583	765	980	1,230
7.8	380	533	701	901	1,140
8.0	314	444	587	758	960

Source: AASHTO *A Policy on Geometric Design of Highways and Streets* 2004

7. Stopping Sight Distance (SSD) Determination – Estimate whether or not the curve provides SSD through the following steps:
    a. Determine the AASHTO Minimum SSD which is found in the AASHTO Minimum Stopping Sight Distance Table (Exhibit 16).
    b. Place one orange traffic cone at the PT of the curve on the edge of the roadway. If a second person is present, that person can temporarily place the traffic cone in the center of the lane during step 7d. However, the edge of the roadway is an appropriate approximation.
    c. Using the measuring wheel, roll out the AASHTO Minimum SSD distance along the edgeline of the roadway towards the PC of the curve (point 1 in Exhibit 15).
    d. At the AASHTO Minimum SSD distance, look back and record whether or not the traffic cone is visible. It is helpful to step into the middle of the inside lane and stoop down so that your eye height is about 3.5′ above the pavement.
    e. Next, place another orange traffic cone at the PC of the curve to mark the location.
    f. Using the measuring wheel, roll out the AASHTO Minimum SSD distance along the edgeline of the roadway towards the PT of the curve and place the third orange traffic cone (point 2 in Exhibit 15) at the edge of the roadway. If a second person is present, that person can temporarily place the traffic cone in the center of the lane during step 7g. However, the edge of the roadway is an appropriate approximation.
    g. Return to the PC of the curve, look back and record whether or not the traffic cone is visible. It is helpful to step into the middle of the inside lane and stoop down so that your eye height is about 3.5′ above the pavement.
    h. If the traffic cone is visible from both locations (PC to 2, and 1 to PT), SSD is provided through the curve unless an obstruction close to the ditch line is present near the center of the curve.
    i. If the traffic cone (2 or PT) is not visible from either location (PC or 1), SSD is not provided through the curve.

Exhibit 15: Stopping Sight Distance Investigation

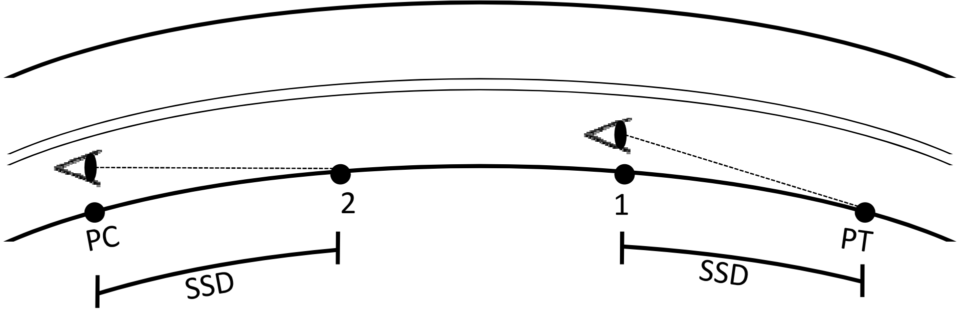


Exhibit 16: AASHTO Minimum Stopping Sight Distance

AASHTO Minimum Stopping Sight Distance Table	
Speed Limit (mph)	Minimum SSD (ft)
15	80
20	115
25	155
30	200
35	250
40	305
45	360
50	425
55	495
60	570
65	645
70	730
75	820
80	910

Source: AASHTO *A Policy on Geometric Design of Highways and Streets* 2004

8. Engineering Judgment – This simple field procedure is aimed at determining mitigation factors for the parameters of radius, superelevation, and stopping sight distance. The field measured radius, superelevation, and stopping sight distance are compared to AASHTO recommended values. Engineering judgment is needed to determine appropriate action based on these measurements and comparisons.

SUMMARY

This research effort aimed to develop a simple procedure using measurement devices readily available that a single engineer can use to determine the radius and superelevation of any horizontal curve. The measurements taken can be applied against a chart to determine the radius. Then, with the superelevation measurement, a determination is made if the curve radius and superelevation meet current design standards for the posted speed limit for the highway. The horizontal SSD can also be checked against current design standards as well, again by only one engineer. Thus, superelevation, radius, and horizontal SSD can be checked against current design standards.

In addition to documenting the field procedure through a MS PowerPoint® presentation, the research team put together a recorded, self-playing presentation using Elluminate *Publish!*® Both the PowerPoint® and self-playing presentations were provided to NCDOT for their future use in training staff on this procedure.

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APPENDIX A: CURVE INVESTIGATION PROCEDURE

Field Investigation Procedure

Simple Field Procedure for Determining Horizontal Curve Radius

Developed Under NCDOT Research Project 2009-09

by

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and

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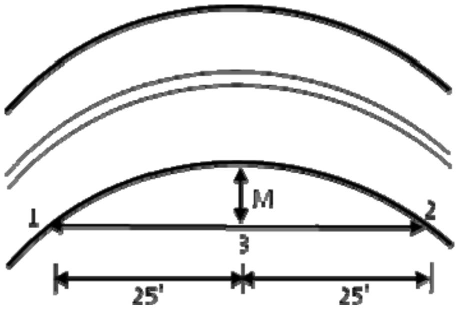
May 31, 2009

Simple Field Procedure for Determining Horizontal Curve Radius

1. Safety and Equipment – Before beginning any field investigation, check that all equipment is available and operable. Although this procedure was developed to minimize exposure to vehicles, some interaction is necessary, so follow NCDOT guidelines for personal safety while implementing this field procedure. Necessary equipment includes:
    a. Safety Vest (Class II or above as required)
    b. Digital Level (4’ long)
    c. Hammer
    d. Masonry Nails (e.g., Parker-Kalon 1½” by ¼”)
    e. Measuring Tape (50’ or 100’ Metal or Cloth, with metal preferred)
    f. Metal Tape Measure (25’)
    g. Clipboard, Field Investigation Form, and Pen
    h. Three Orange Traffic Cones (2’ tall)
    i. Measuring Wheel

2. General Curve Investigation – Determine the limits (Point of Curvature, PC, and Point of Tangency, PT) of the curve through visual observations of the tangent sections leading into and out of the curve. All measurements should occur within these limits of the curve. Try to locate representative areas of the curve to conduct your measurements, avoiding any abnormalities. The first measurement should be about in the middle of the curve.

3. Measurement of Middle Ordinate – Determine the middle ordinate measurement through the following steps:
    a. Place nails in the pavement on the outside edge of the edgeline stripping 50’ apart (at points 1 and 2 in the figure). One nail can be used to hold the hook at the end of the 50’ measuring tape and the second nail can be used to pull the tape against or around (if cloth tape is used). The tape must be pulled taught and remain straight for step 3b.
    b. Measure the middle ordinate distance at the middle point of the tape (25’), using the smaller tape measure (at point 3 in the figure). The distance M should be read and recorded to the nearest 1/8”.
    c. Repeat this measurement by moving points 1 and 2 together about 10 feet left and then 10 feet right of the first measurement. This provides three measurements.



4. Measurement of Superelevation – Determine the superelevation of the curve by measuring the superelevation of the roadway perpendicular to the direction of travel by reading and recording five measurements that are representative of the superelevation of the middle section of the curve in each lane. Circle the median value, which will be used as the superelevation value. This value must be in increments of 0.2% as represented in the AASHTO Minimum Radius Tables. If necessary, round the field measured value up or down to the nearest 0.2% increment.

5. Radius Determination – Determine the radius of the curve by using the circled middle ordinate value from the Field Investigation Form and the Middle Ordinate Conversion Table. Add the inside lane width to the table value to determine the centerline radius of the curve. Record the value on the Field Investigation Form.

6. AASHTO Minimum Radius Determination – Determine the minimum recommended radius of the curve by using the circled superelevation value from the Field Investigation Form and the appropriate AASHTO Minimum Radius Table (for an e_{max} of either 4%, 6%, or 8%). Record the value on the Field Investigation Form. The AASHTO Minimum Radius for the inside lane and outside lane will be equal if the superelevations for each lane are equal.

   The selection of the appropriate e_{max} value is important. Shoulder sections of two-lane roadways should have a design superelevation of 8% for higher speed segments or 6% for lower speed segments. The comparison can be examined for both design superelevations, if necessary. A design superelevation of 4% should be used for curb and gutter sections of urban roadways. Additional maximum superelevation rate guidance is available from the NCDOT Roadway Design Manual – Part 1, Chapter 1: General Design.

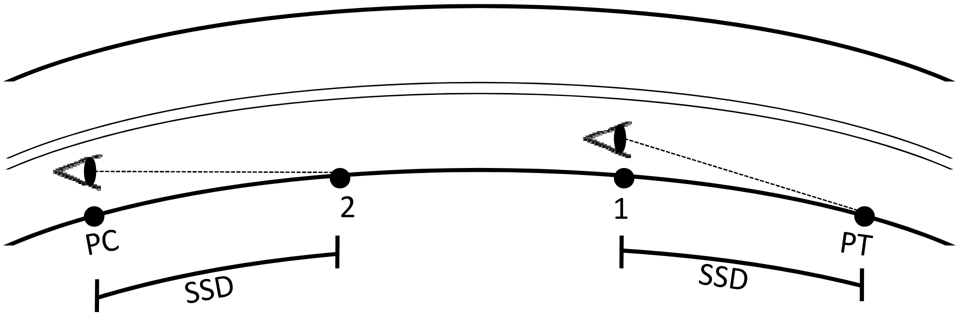
7. Stopping Sight Distance (SSD) Determination – Estimate whether or not the curve provides SSD through the following steps:
   a. Determine the AASHTO Minimum SSD which is found in the AASHTO Minimum Stopping Sight Distance Table.
   b. Place one orange traffic cone at the PT of the curve on the edge of the roadway. If a second person is present, that person can temporarily place the traffic cone in the center of the lane during step 7d. However, the edge of the roadway is an appropriate approximation.
   c. Using the measuring wheel, roll out the AASHTO Minimum SSD distance along the edgeline of the roadway towards the PC of the curve (point 1 in the figure).
   d. At the AASHTO Minimum SSD distance, look back and record whether or not the traffic cone is visible. It is helpful to step into the middle of the inside lane and stoop down so that your eye height is about 3.5’ above the pavement.
   e. Next, place another orange traffic cone at the PC of the curve to mark the location.
   f. Using the measuring wheel, roll out the AASHTO Minimum SSD distance along the edgeline of the roadway towards the PT of the curve and place the third orange traffic

cone (point 2 in the figure) at the edge of the roadway. If a second person is present, that person can temporarily place the traffic cone in the center of the lane during step 7g. However, the edge of the roadway is an appropriate approximation.

g. Return to the PC of the curve, look back and record whether or not the traffic cone is visible. It is helpful to step into the middle of the inside lane and stoop down so that your eye height is about 3.5’ above the pavement.

h. If the traffic cone is visible from both locations (PC to 2, and 1 to PT), SSD is provided through the curve unless an obstruction close to the ditch line is present near the center of the curve.

i. If the traffic cone (2 or PT) is not visible from either location (PC or 1), SSD is not provided through the curve.



8. Engineering Judgment – This simple field procedure is aimed at determining mitigation factors for the parameters of radius, superelevation, and stopping sight distance. The field measured radius, superelevation, and stopping sight distance are compared to AASHTO recommended values. Engineering judgment is needed to determine appropriate action based on these measurements and comparisons.

Field Investigation Form

Investigator:

Date:

Location:

Posted Speed Limit:

Middle Ordinate Measurements

Measurement 1:	Measurement 2:	Measurement 3:
inches	inches	inches

Circle the median value above, this should be used as the middle ordinate measurement in the Middle Ordinate Conversion Table to determine the radius. Record the radius value below.

Radius:

Inside Lane Superelevation Measurements

Measurement 1:	Measurement 2:	Measurement 3:	Measurement 4:	Measurement 5:
%	%	%	%	%

Outside Lane Superelevation Measurements

Measurement 1:	Measurement 2:	Measurement 3:	Measurement 4:	Measurement 5:
%	%	%	%	%

Circle the median value above for the inside and outside lanes. Tthese should be used as the superelevation measurement in the AASHTO Radius Table to determine the AASHTO minimum radius. Select the e_{max} and record the minimum radius values below based on the superelevation of both lanes.

e_{max}:	4.0% (for curb & gutter segments)	Inside Lane AASHTO Minimum Radius, R_{min}:
		Outside Lane AASHTO Minimum Radius, R_{min}:
e_{max}:	6.0% (for lower speed shoulder segments)	Inside Lane AASHTO Minimum Radius, R_{min}:
		Outside Lane AASHTO Minimum Radius, R_{min}:
e_{max}:	8.0% (for higher speed shoulder segments)	Inside Lane AASHTO Minimum Radius, R_{min}:
		Outside Lane AASHTO Minimum Radius, R_{min}:

Stopping Sight Distance Measurements

AASHTO Minimum SSD:	Is cone visible at PC from AASHTO Minimum SSD?	Yes	No
feet	Is cone visible at PT from AASHTO Minimum SSD?	Yes	No

Circle the appropriate response for cone visibility from the PC and PT. Use the AASHTO Minimum Stopping Sight Distance Table to determine the AASHTO Minimum SSD.

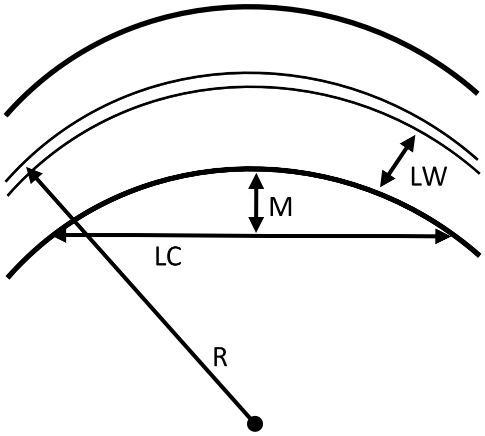
Notes

Middle Ordinate Conversion Table

Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft	Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft	Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft	Middle Ordinate, M (in)	Radius (ft) for a Long Chord of 50 ft
0.125	30,000	2.625	1,429	5.25	715	10.25	366
0.250	15,000	2.750	1,364	5.50	682	10.50	358
0.375	10,000	2.875	1,304	5.75	652	10.75	349
0.500	7,500	3.000	1,250	6.00	625	11.00	341
0.625	6,000	3.125	1,200	6.25	600	11.25	334
0.750	5,000	3.250	1,154	6.50	577	11.50	327
0.875	4,286	3.375	1,111	6.75	556	11.75	320
1.000	3,750	3.500	1,072	7.00	536	12.00	313
1.125	3,333	3.625	1,035	7.25	518	12.25	307
1.250	3,000	3.750	1,000	7.50	500	12.50	301
1.375	2,727	3.875	968	7.75	484	12.75	295
1.500	2,500	4.000	938	8.00	469	13.00	289
1.625	2,308	4.125	909	8.25	455	13.25	284
1.750	2,143	4.250	883	8.50	442	13.50	278
1.875	2,000	4.375	857	8.75	429	13.75	273
2.000	1,875	4.500	834	9.00	417	14.00	268
2.125	1,765	4.625	811	9.25	406	14.25	264
2.250	1,667	4.750	790	9.50	395	14.50	259
2.375	1,579	4.875	769	9.75	385	14.75	255
2.500	1,500	5.000	750	10.00	375	15.00	251

Note: Add inside lane width to radius value from table to find centerline radius for a two-lane highway.

To find the radius of a curve with any chord length, the following equation can be used:



$$R = \frac{M^2 + 0.25LC^2}{2M} + LW$$

Where:

R = Radius (feet)

M = Middle Ordinate (feet)

LW = Lane Width (feet)

LC = Long Chord (feet)

AASHTO Minimum Radius Table (e_{max} = 4%)

Superelevation, e (%)	Posted Speed Limit, V_d (mph)				
	35	40	45	50	55
	Radius (ft)				
1.5	3,730	4,770	5,930	7,220	8,650
2.0	2,490	3,220	4,040	4,940	5,950
2.2	2,120	2,760	3,480	4,280	5,180
2.4	1,760	2,340	2,980	3,690	4,500
2.6	1,420	1,930	2,490	3,130	3,870
2.8	1,170	1,620	2,100	2,660	3,310
3.0	982	1,370	1,800	2,290	2,860
3.2	835	1,180	1,550	1,980	2,490
3.4	714	1,010	1,340	1,720	2,170
3.6	610	865	1,150	1,480	1,880
3.8	512	730	970	1,260	1,600
4.0	371	533	711	926	1,190

Source: AASHTO *A Policy on Geometric Design of Highways and Streets* 2004

AASHTO Minimum Radius Table (e_{max} = 6%)

Superelevation, e (%)	Posted Speed Limit, V_d (mph)				
	35	40	45	50	55
	Radius (ft)				
1.5	4,100	5,230	6,480	7,870	9,410
2.0	2,950	3,770	4,680	5,700	6,820
2.2	2,630	3,370	4,190	5,100	6,110
2.4	2,360	3,030	3,770	4,600	5,520
2.6	2,130	2,740	3,420	4,170	5,020
2.8	1,930	2,490	3,110	3,800	4,580
3.0	1,760	2,270	2,840	3,480	4,200
3.2	1,600	2,080	2,600	3,200	3,860
3.4	1,460	1,900	2,390	2,940	3,560
3.6	1,320	1,740	2,190	2,710	3,290
3.8	1,190	1,590	2,010	2,490	3,040
4.0	1,070	1,440	1,840	2,300	2,810
4.2	960	1,310	1,680	2,110	2,590
4.4	868	1,190	1,540	1,940	2,400
4.6	788	1,090	1,410	1,780	2,210
4.8	718	995	1,300	1,640	2,050
5.0	654	911	1,190	1,510	1,890
5.2	595	833	1,090	1,390	1,750
5.4	540	759	995	1,280	1,610
5.6	487	687	903	1,160	1,470
5.8	431	611	806	1,040	1,320
6.0	340	485	643	833	1,060

Source: AASHTO *A Policy on Geometric Design of Highways and Streets* 2004

AASHTO Minimum Radius Table (e_{max} = 8%)

Superelevation, e (%)	Posted Speed Limit, V_d (mph)				
	35	40	45	50	55
	Radius (ft)				
1.5	4,260	5,410	6,710	8,150	9,720
2.0	3,120	3,970	4,930	5,990	7,150
2.2	2,800	3,570	4,440	5,400	6,450
2.4	2,540	3,240	4,030	4,910	5,870
2.6	2,320	2,960	3,690	4,490	5,370
2.8	2,130	2,720	3,390	4,130	4,950
3.0	1,960	2,510	3,130	3,820	4,580
3.2	1,820	2,330	2,900	3,550	4,250
3.4	1,690	2,170	2,700	3,300	3,970
3.6	1,570	2,020	2,520	3,090	3,710
3.8	1,470	1,890	2,360	2,890	3,480
4.0	1,370	1,770	2,220	2,720	3,270
4.2	1,280	1,660	2,080	2,560	3,080
4.4	1,200	1,560	1,960	2,410	2,910
4.6	1,130	1,470	1,850	2,280	2,750
4.8	1,060	1,390	1,750	2,160	2,610
5.0	991	1,310	1,650	2,040	2,470
5.2	929	1,230	1,560	1,930	2,350
5.4	870	1,160	1,480	1,830	2,230
5.6	813	1,090	1,390	1,740	2,120
5.8	761	1,030	1,320	1,650	2,010
6.0	713	965	1,250	1,560	1,920
6.2	669	909	1,180	1,480	1,820
6.4	628	857	1,110	1,400	1,730
6.6	590	808	1,050	1,330	1,650
6.8	553	761	990	1,260	1,560
7.0	518	716	933	1,190	1,480
7.2	485	672	878	1,120	1,400
7.4	451	628	822	1,060	1,320
7.6	417	583	765	980	1,230
7.8	380	533	701	901	1,140
8.0	314	444	587	758	960

Source: AASHTO *A Policy on Geometric Design of Highways and Streets* 2004

AASHTO Minimum Stopping Sight Distance Table

Speed Limit (mph)	Minimum SSD (ft)
15	80
20	115
25	155
30	200
35	250
40	305
45	360
50	425
55	495
60	570
65	645
70	730
75	820
80	910

Source: AASHTO *A Policy on Geometric Design of Highways and Streets* 2004

APPENDIX B: CURVE INVESTIGATION EXAMPLE

Field Investigation Form

Investigator: John Smith

Date: 2/11/2009

Location: A Street (0.1 miles North of B Street)

Posted Speed Limit: 45 MPH

Middle Ordinate Measurements

Measurement 1:	Measurement 2:	Measurement 3:
8 $^{1}/_{8}$ inches	[✓ 8 $^{1}/_{4}$] inches	9 $^{5}/_{8}$ inches

Circle the median value above, this should be used as the middle ordinate measurement in the Middle Ordinate Conversion Table to determine the radius. Record the radius value below.

Radius: 455' + 10' (Lane Width) = 465'

Inside Lane Superelevation Measurements

Measurement 1:	Measurement 2:	Measurement 3:	Measurement 4:	Measurement 5:
[✓ 8.2 %]	8.0 %	8.4 %	8.4 %	8.0 %

Outside Lane Superelevation Measurements

Measurement 1:	Measurement 2:	Measurement 3:	Measurement 4:	Measurement 5:
8.0 %	7.8 %	[✓ 7.8 %]	7.6 %	7.8 %

Circle the median value above for the inside and outside lanes. These should be used as the superelevation measurement in the AASHTO Radius Table to determine the AASHTO minimum radius. Select the e_{max} and record the minimum radius values below based on the superelevation of both lanes.

e_{max}:	4.0% (for curb & gutter segments)	Inside Lane AASHTO Minimum Radius, R_{min}:	
		Outside Lane AASHTO Minimum Radius, R_{min}:	
e_{max}:	6.0% (for lower speed shoulder segments)	Inside Lane AASHTO Minimum Radius, R_{min}:	
		Outside Lane AASHTO Minimum Radius, R_{min}:	
e_{max}:	[✓ 8.0% (for higher speed shoulder segments)]	Inside Lane AASHTO Minimum Radius, R_{min}:	587'
		Outside Lane AASHTO Minimum Radius, R_{min}:	701'

Stopping Sight Distance Measurements

AASHTO Minimum SSD:		
360 feet	Is cone visible from PC to AASHTO Minimum SSD?	Yes [✓ No]
	Is cone visible at PT from AASHTO Minimum SSD?	Yes [✓ No]

Circle the appropriate response for cone visibility from the PC and to the PT. Use the AASHTO Minimum Stopping Sight Distance Table to determine the AASHTO Minimum SSD.

Notes

Existing curve radius < Rmin and SSD sight line check failed on both ends of the curve.